PERFORMANCE OF ULTRASONIC EQUIPMENT FOR PAVEMENT THICKNESS MEASUREMENT AND OTHER HIGHWAY APPLICATIONS

FINAL REPORT

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BY

C. F. SCHOLER

JHRP

JOINT HIGHWAY RESEARCH PROJECT
PURDUE UNIVERSITY AND
INDIANA STATE HIGHWAY COMMISSION

Final Report

PERFORMANCE OF ULTRASONIC EQUIPMENT FOR PAVEMENT THICKNESS MEASUREMENT AND OTHER HIGHWAY APPLICATIONS

TO: J.F. McLaughlin, Director
Joint Highway Research Project

FROM: Harold L. Michael, Associate Director
Joint Highway Research Project

July 16, 1970
File No.: 5-15-3
Project No.: C-36-61C

The attached report entitled "Performance of Ultrasonic Equipment for Pavement Thickness and other Highway Applications" is the final report of the project by that name. This report was prepared by Dr. Charles F. Scholer of our staff and utilized work done by Dr. D. Ravina and Mr. R.D. Pavlovich also of our staff.

It is concluded that the equipment is not satisfactory for measuring pavement thickness.

In considering other applications it was found to be useful in determining the continuety of concrete in a structure such as in a survey of a bridge deck to determine areas with deteriorated concrete or incipient spalling. It was determined that reinforcing steel up to six percent by volume did not influence pulse velocity values for the concrete.

Use of pulse velocity for evaluating quality of fresh concrete was investigated and was not found promising for practical control of concrete in constructions.

The report is submitted to the Board for the record and for acceptance as fulfillment of the objectives of the research.

Respectfully submitted,

Harold L Michael

Harold L. Michael
Associate Director

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by

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Joint Highway Research Project
Project: C-36-61C
File: 5-15-3

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Conducted by

Joint Highway Research Project
Engineering Experiment Station
Purdue University

in cooperation with the

Indiana State Highway Commission

and the

U.S. Department of Transportation
Federal Highway Administration
Bureau of Public Roads

The opinions, findings and conclusions expressed in this publication are those of the authors and not necessarily those of the Bureau of Public Roads

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Not Reviewed By
Indiana State Highway Commission
or the
Bureau of Public Roads

Purdue University
Lafayette, Indiana
July 16, 1970

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Abstract

A final report on a project conducted by the Joint Highway Research Project at Purdue University in cooperation with the Indiana State Highway Commission and the Federal Highway Administration entitled "Performance of Ultrasonic Equipment for Pavement Thickness Measurement and Other Highway Applications." A progress report, JHRP No. 14, July 1968, dealt with the evaluation of the equipment for pavement thickness measurements. A condensation of said report is included as part of this final report.

The equipment used was a soniscope and an associated frequency generator and counter for determining resonant frequency through the depth of the pavement slab. It was concluded that the equipment is not satisfactory for measuring pavement thickness.

In considering other applications it was found to be useful in determining the continuety of concrete in a structure such as in a survey of a bridge deck to determine areas with deteriorated concrete or incipient spalling.

Use of pulse velocity for evaluating quality of fresh concrete was investigated and was not found promising for practical control of concrete in constructions.

A laboratory investigation of the effect reinforcing steel has on pulse velocity measurements was conducted with steel varying from 0 to 6 percent of the volume. It was concluded that reinforcing steel does not influence pulse velocity when the pulse measuring path crosses the steel as would usually be the case in reinforced concrete columns, slabs and beams.

Introduction

This project was conducted in order to test and evaluate two pieces of equipment, the James Model C-4960 Ultrasonic V-Scope, and the Model C-4959 Ultrasonic E-Meter with accessory equipment for each (as supplied by James Electronics, Inc., 4050 North Rockwell Street, Chicago, Illinois).

The V-Scope measures pulse velocity and is what is conventionally called a soniscope in the literature, (1,2, 3,4). The E-Meter is a frequency generator with a digital display which can easily be connected to the V-scope to utilize the cathode tube of the V-scope for identification of resonant frequencies.

The primary purpose was to measure its usefulness, accuracy and cost when used jointly as a means of non-destructively determining pavement thickness. A careful comparison was made of thicknesses determined by this non-destructive procedure to that of both known pavement thicknesses and that obtained by conventional procedures (core drilling) on actual pavements.

A secondary purpose was to consider potential uses of this same equipment for other highway uses. The other applications were almost exclusively confined to those associated with concrete. Other highway materials (with the exception of rock and wood) are not amenable to meaningful field tests with these two instruments. This does not necessarily preclude similar types of instruments from having application to such materials.

Pavement Thickness Measurements

The results of the "Evaluation of the Performance of Ultrasonic Equipment for Pavement Thickness Measurements" was reported in a progress report with that title by C.F. Scholer and R.D. Pavlovich in July 1968. They are repeated in a slightly revised form in this final report however readers wishing to study the tabulations of data should refer to the appendices of the July 1968 progress report.

The pulse velocity and longitudinal resonant frequency in the thickness direction are determined by use of the ultrasonic equipment. Thickness is calculated by the relationship proposed by Muenow, (5)

$$t = \frac{V_P}{2N_R}$$

where t = slab thickness (an average over an area approximately 3 feet in diameter)

V_P = pulse velocity through the slab

N_R = longitudinal resonant frequency of the slab

Field power (120 V a.c.) was provided by installing an a.c. inverter in a small station-wagon type van thus establishing a mobile and completely self contained unit.

Two series of tests are reported; one set consists of measurements of thickness of control slabs at the ISHC Research Training Center and the other set was run on actual pavement slabs in the field.

Figure 1 shows the arrangement and acutal thickness of control slabs at the Research and Training Center.

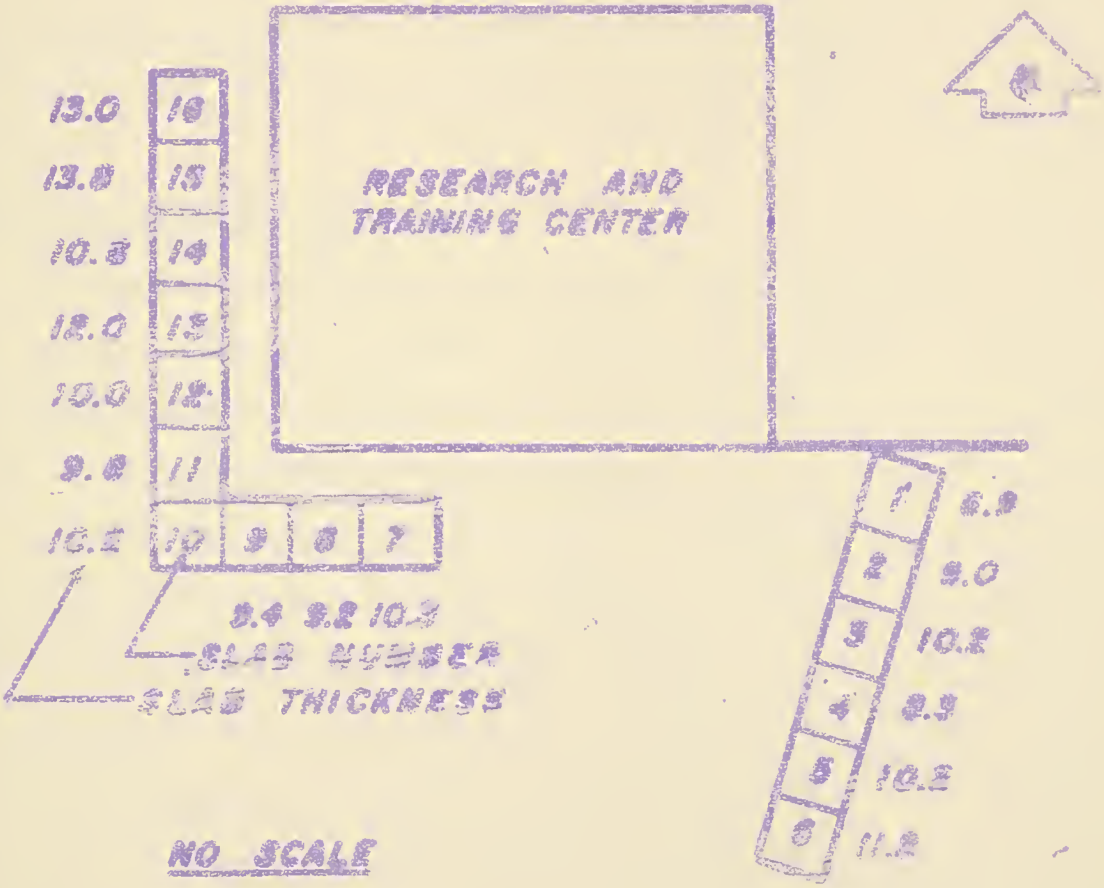


FIGURE 1. SCHEMATIC DIAGRAM SHOWING THE LAYOUT AND THICKNESS OF 5'x5' TEST SLABS AT I.E.M.C. RESEARCH AND TRAINING CENTER.

Field test locations were:

1. I-465; Indianapolis
2. U.S. 40; Terre Haute
3. U.S. 50; Versailles
4. I-70; Knightstown
5. I-65; Haubstadt

Sonic thickness measurements of pavement slabs were compared, at the site, with ISHC cores that were taken from the same location.

Summary of Results and Conclusions

The technique used does not consistently provide sufficient precision to justify use as a means of determining thickness of pavement slabs. The influence of the base course is a factor in the applicability of the technique.

Figure 2 shows a best fit line through data obtained from test slabs and Figure 3 shows cumulative number of tests versus percent error for all tests conducted.

It should be noted that only about 40 percent of the tests provide precision of ± 5 percent; this error amounts to a deviation of one half inch for a ten inch pavement slab. Figure 4 shows a plot of sonic thickness versus actual thickness for all measurements. ± 5 percent limits are included to show scatter of these data.

Table I is a tabulation of reduced data from the test slabs and Figure 5 is a plot of average sonic thickness versus actual slab thickness.

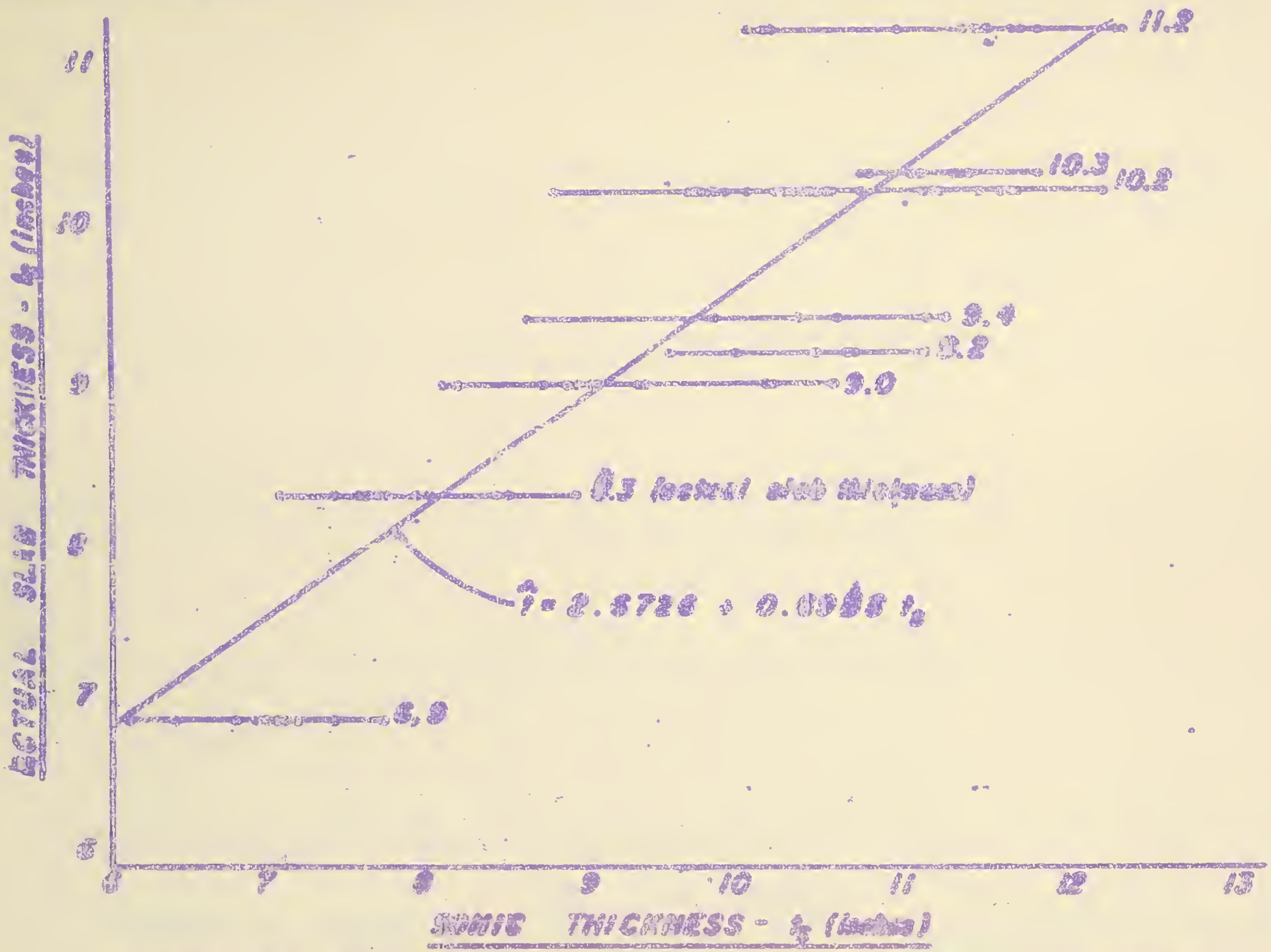


FIGURE 2. SONIC THICKNESS (t_s) VS. ACTUAL THICKNESS (t_a) FOR TEST SLABS.

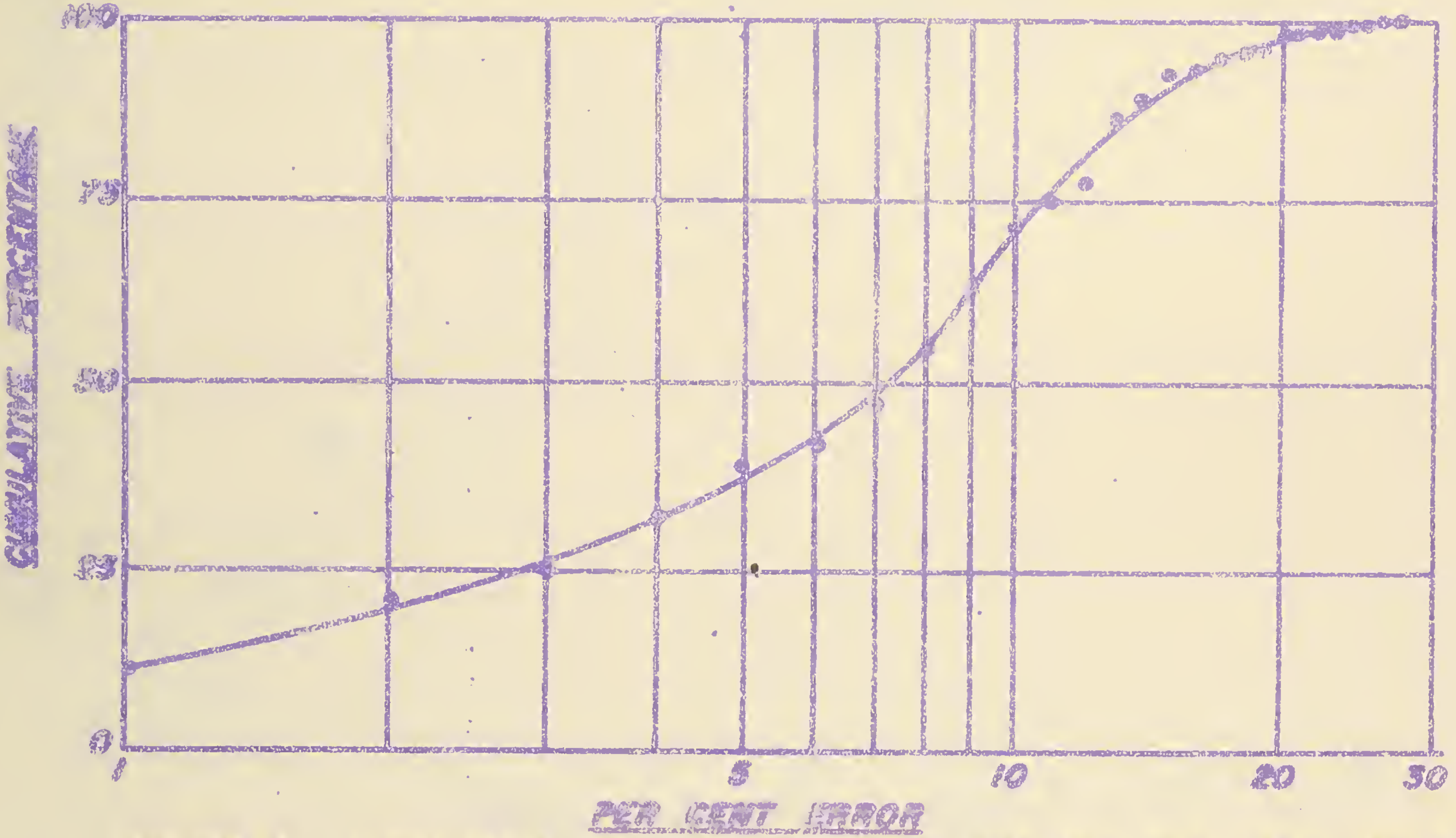


FIGURE 3. CUMULATIVE PERCENTAGE CURVE FOR THE PER CENT ERROR IN THICKNESS MEASUREMENTS OF TEST SLABS AND PAVEMENTS.

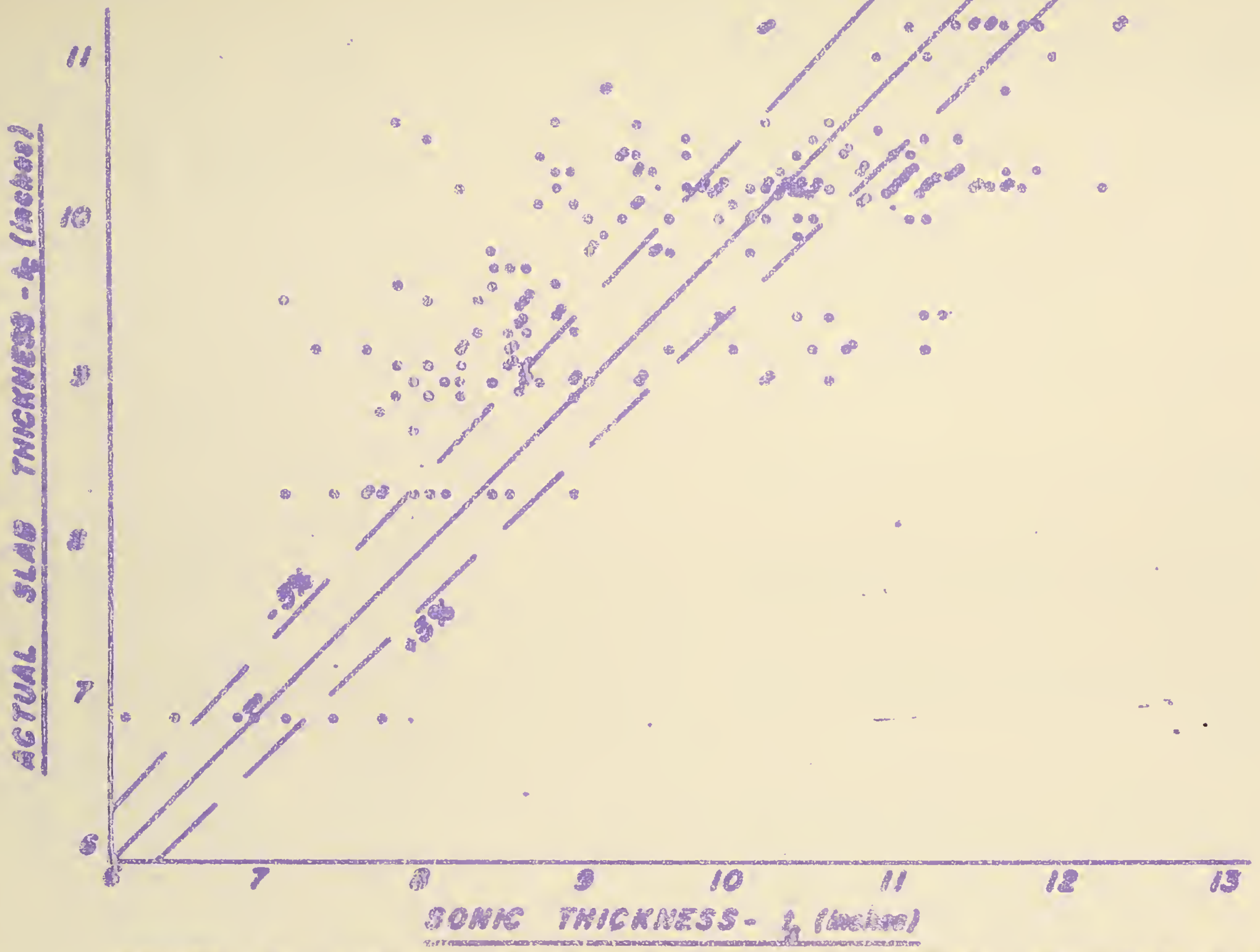


FIGURE 4. SONIC THICKNESS (t_s) VS. ACTUAL THICKNESS (t_a) FOR TEST SLABS AND PAVEMENT.

TABLE I

INDIVIDUAL TEST SLAB DATA

n = no. observations

t_s = average sonic thickness

$$s_{ts}^2 = \frac{n \quad t_s^2 - (\quad t_s)^2}{n\,(n-1)}$$

Slab (t_c)	n	Et_s^2	Et_s	s_{ts}^2	s_{ts}	(Ave.) ts	Range
6.9	10	483.48	69.4	0.20	0.45	6.9	6.1 - 7.7
8.3	12	753.31	94.9	0.26	0.51	7.9	7.1 - 8.9
9.0	12	1016.21	110.1	0.55	0.74	9.2	8.1 - 10.5
9.2	6	644.35	62.1	0.32	0.57	10.4	9.5 - 11.1
9.4	6	634.99	61.5	0.92	0.96	10.2	8.6 - 11.2
10.2	26	2871.99	272.5	0.63	0.79	10.5	8.8 - 12.2
10.3	8	993.29	89.1	0.13	0.36	11.1	10.7 - 11.8
11.2	14	1809.21	158.9	0.44	0.66	11.4	10.0 - 12.3

Discussion

A brief introduction to the principles of operation of this equipment is included to show why errors are introduced and perhaps how these can be overcome.

Thickness determination is based on measuring two parameters: pulse velocity and slab resonant frequency. Pulse velocity is the speed that sound travels through a material and resonant frequency is that condition where the slab will have a maximum vibration for a given force. There are three basic resonant frequencies: longitudinal, flexural, and torsional. We measured the longitudinal resonant frequency in the thickness dimension.

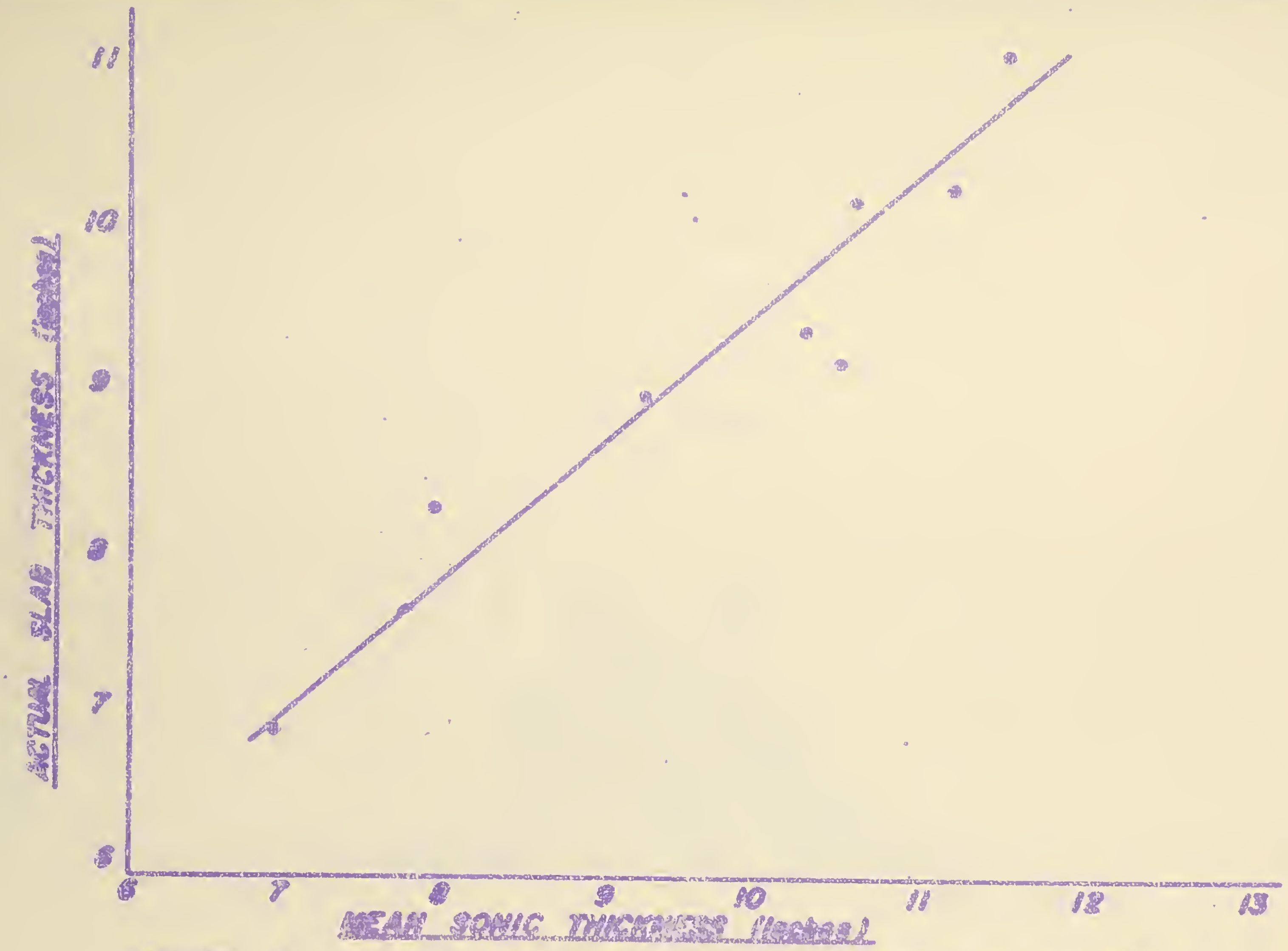


FIGURE 5. MEAN SONIC THICKNESS VS. ACTUAL THICKNESS FOR TEST SLABS.

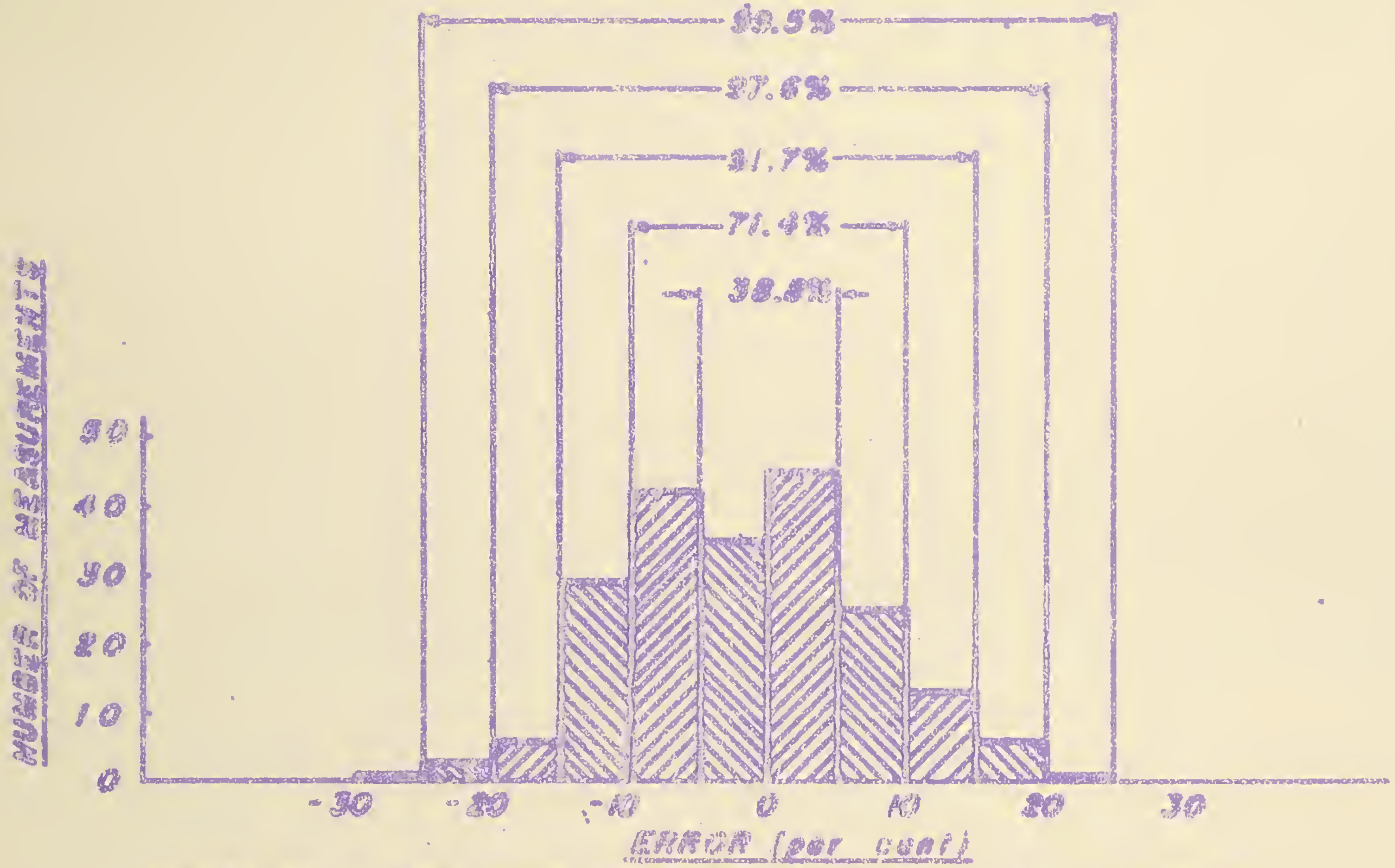


FIGURE 6. PER CENT ERROR DISTRIBUTION FOR TEST SLABS AND PAVEMENTS.

The heart of the measuring system is a transducer that will convert mechanical energy (vibrations) to measurable electrical energy or vice versa. Piezoelectric crystals (Rochelle salts in this equipment) exhibit the property that when compressed they emit an electrical impulse. Conversely when an electrical charge is imposed on the crystal, it responds by dilating or compressing. The equipment then functions by detecting and measuring the current emitted from the crystals or by electrically exciting these crystals thus causing them to vibrate.

One other property of a piezoelectric material worthy of note is the Curie point. At some temperature, dilations or compression of the crystal will produce no current or it will be so low as to not be measurable with ordinary amplification. If the Curie point is sufficiently above normal operating conditions no problems of loss of sensitivity arise. However, the transducers for the instruments used for this study commenced to show losses in response at temperatures above 90°F. Solution of this problem consisted of artificial cooling by simply storing in an ice chest when not in use and by using cooled couplant fluid. There are also synthetic piezoelectric materials that have Curie points at temperatures considerably higher than those which would be encountered on highway pavements. Their use, however, is limited because of their low power efficiency.

Pulse velocity is determined by placing driving and receiving transducers a known distance apart and measuring the time, in microseconds, it takes a pulse to travel between them through the concrete.

The "V-Scope" functioned very well and provided good, reproducible measurements of the pulse velocity of concretes. It should be mentioned that pulse velocity of concrete is a function of several variables including moisture content, paste aggregate ratio, air content, type of aggregate, paste porosity and deterioration of the concrete. Therefore, one cannot assume that pulse velocity, once determined, will remain a constant value throughout a pavement.

The other parameter, resonant frequency, is not as simple to determine as is pulse velocity. The concept of resonance as applied to pavement slabs is as follows:

Resonance is measured by driving and receiving transducers placed side by side on the surface. By means of a variable frequency generator the driving transducer excites through a frequency spectrum from 2 to 20 KC and concurrently the receiving transducer's output is monitored for maximum response indicative of the slabs maximum amplitude of vibration.

The determination of resonant frequency with this technique was most difficult. The correct identification of the true resonant frequency of the actual slab thickness was often masked by too many spurious responses through the frequency range.

The cause of the spurious responses is believed to be the transducers which themselves have resonant frequencies of their own depending upon their size and shape.

Operation and Maintenance in the Field

The electrical portion of this measuring system is very stable, portable and rugged. Mechanical and electrical malfunctions were rare, minor, and easily repaired. Exposure to field conditions and field use, except for the transducers temperature susceptibility, presented no problem to adequate functioning of the instruments.

Operation of the instruments is simple and should be able to be taught to a technician in a matter of three or four hours. Interpretation of output from the cathode ray tube for both instruments is easily interpreted with the exception of the spurious resonant responses.

Core Sampling and Sonic Techniques Compared

Due to variations in determining resonant frequency, four sonic measurements were made at each core location. Times for making sonic determinations were about the same as those involved in obtaining a core sample with the drill crew occasionally working faster on green concrete or on those with softer aggregates. It is the opinion of the investigators that without the difficulties encountered in identifying the true resonant frequency of the slab thickness, production rates could be from three to five times that of conventional drilling operations.

The sonic methods followed involved two persons and one vehicle whereas core sampling includes two to three persons, a drill rig plus one to two other vehicles. It is not necessary for the vehicle on the sonic method to be on the pavement thus enabling earlier thickness determinations.

It was observed that if a second core was obtained within a relatively close distance to the first, say three or four feet, differences of one half inch between core lengths could be measured. Sonic gear on the other hand averages the thickness of a circle of approximately three feet in diameter.

Other Highway Applications

Resonant Frequency Tests and Determination of Dynamic Youngs Modulus

The E-Meter serves as an excellent frequency generator and readout hence when used in conjunction with the cathode tube in the V-Scope it may conveniently be used to perform Tests for Fundamental Frequencies of Concrete, ASTM, C-215. These results, as described in the ASTM C-215, may be utilized to calculate the dynamic Young's modulus of elasticity of a specimen providing that the size and weight of the specimen are accurately known, a reasonable value for Poisson's ratio assumed and dimensions are of proper proportions for the test procedure.

The V-Scope provides the pulse velocity measurement which may also be used to determine the dynamic Youngs modulus as discussed by Whitehurst (6) and using an equation first proposed by Long et al (7), $E = V^2\rho\ (1 + \mu)\ (1 - 2\mu)\ (1 - \mu)$ where E = dynamic Young's modulus of elasticity, V = longitudinal pulse velocity, ρ = density and μ = Poisson's ratio. The advantage of using pulse velocity for determination of E is that it is not limited to specimens hence can be used in the field as a truly non-destructive method of evaluating a mechanical property of a material in the direction through which the pulse travels.

This points out that for a material such as wood, whose E differs depending upon the orientation of its structure, different pulse paths enable each of the different E values to be measured. This has considerable use in evaluating wood structures.

Pulse Velocity as a Measure of Concrete Quality

Pulse velocity is a function of the concrete's dynamic Young's modulus of elasticity and of the continuity of the concrete. Compressive strength and modulus of elasticity of concrete are separate properties hence one cannot accurately be predicted from the other. At lease not insofar as pulse velocity, as a function of the modulus of elasticity, being a satisfactory prediction of compressive strength (2,6).

Even with the compressive strength not being predictable by pulse velocity the prospect existed that pulse velocity might be a rapid and non-destructive field measure of concrete quality and uniformity. This would require the pulse velocity being previously correlated in a laboratory for a mix of the same proportion. This possibility of this use of the equipment warrented a laboratory investigation.

The investigation was designed to show if deviations in the mix proportion could be easily ascertained in either the fresh or hardened condition of the concrete. The mix proportions are given in Table 2. All concretes were without entrained air, made with Type I cement from the same mill grind and the coarse aggregate was gravel of laboratory identification 79-1G as was the sand. All mixing was done in a 1½ cubic foot pan mixer.

Mixes A, B, and C investigate effect of variations in the proportioning of the aggregate. Design mix A is a conventional six bag mix while mixes B and C have greater

proportions of sand. B is 50 percent sand and 50 percent coarse aggregate while C has 37 percent coarse aggregate and 63 percent sand a reversal of the proportion in mix A.

Mixes A, D, E, and F have the coarse aggregate constant while the cement content is varied. Since the water content remains the same the water cement ratio varies from 0.80 in mix D to 0.45 in mix F. Sand quantity was adjusted for changes in quantity of cement.

Mix G is a high temperature, 35°C, repeat of mix A.

Pulse transmissions were made through the cylinder from top to bottom. Paraffin coated paper molds with metal bottom caps were used and conformed to requirements of ASTM C470-677. With the equipment of this study it was not possible to make pulse measurements throughout the early period of hydration however at the approximately 3 hours age it became possible to measure a pulse transmission time. Modification of the equipment for this purpose might allow for determination of pulse velocity at any age from time of molding.

The results of the pulse transmission time measurements are given in Tables 3 through 9. Three or four specimens from each batch were used for time measurements in the first 24 hours. At later ages lesser numbers from each batch were tested.

TABLE 2

MIX PROPORTIONS FOR CONCRETE USED IN LABORATORY PULSE VELOCITY INVESTIGATIONS

Design Mix	A	B	C	D	E	F	G*	H
Cement	564	564	564	376	470	658	564	564
Water	300	300	300	300	300	300	300	313**
Coarse Aggregate								1590***
1"	295	230	170	295	295	295	295	
3/4"	430	325	240	430	430	430	430	
1/2"	600	490	360	600	600	600	600	
No. 4	745	590	430	745	745	745	745	
(Total C.A.)	(2070)	(1635)	(1200)	(2070)	(2070)	(2070)	(2070)	
Sand	1200	1635	2070	1360	1280	1120	1200	1460
(Total Batch Wt.)	(4134)	(4134)	(4134)	(4106)	(4120)	(4148)	(4134)	(3998)

*Materials were warmed prior to mixing so that temperature of mixed concrete was initially 35°C.

**Water Reducing Admixture used to give slump of 4 inches.

***3/4" Maximum aggregate size, Indiana State Highway Specification No. 9.

TABLE 3

PULSE VELOCITY & COMPRESSIVE STRENGTHS AT DIFFERENT AGES

DESIGN MIX A

Batch	Unit Wt.	Slump	Cylinder #	Age, hrs.	3	3½	5	5½	6½	7½	9½	24 hrs	24	2 day	3 day	7 day	28 day
								(with mold)									
						Transmission Time in microseconds											
1	153.6	5.0 inches	1		389	338	202	182	153	146	134	106	97	95	93	[2,220]	
			2		410	333	197	186	160	147	137	106	102	95	93	95 [3,240]	
			3		395	341	196	178	153	144	132	100	100 [1,340]			96	[3940]
			4			318	202	178	161	150	138	104	101			93 [2,600]	90
			5	Average Pulse Velocity ft/sec	(2510)	(3000)	(5020)	(5530)	(6320)				101	(10,520)	(10,750)		90 [4190]
			6										100 [1,520]				90 [4130] (9620)
					2-3/4hr	3	4½	5	6	7	8						
2	152.6	5.0 inches	7		600	502	276	215	176	153	148	102	100	95	93		
			8		525	455	233	201	170	153	143	102	100	95	93	[2,100]	
			9		590	485	255	211	181	159	148	102	99			[2,730]	
			10		530	495	274	225	183	162	150	101	100			93	
			11	Average Pulse Velocity	(1780)	(2060)	(3850)	(4700)	(5620)	(6370)	(6800)		91	(10,520)	(10,750)	(10,630)	104* [3,110]

☆ Values within brackets are compressive strengths, psi, of cylinders broken at the given age.

*roomdried after 7 da.

TABLE 4

PULSE VELOCITY & COMPRESSIVE STRENGTHS AT DIFFERENT AGES

DESIGN MIX B

Batch	Unit Wt.	Slump	Cylinder #	Age, hrs	3½	4⅓	5½	7	8⅓	24 hrs	3 day	7 day	28 day	440 day
				Transmission Time in Microseconds										
1	151.1	3.5 inches	1		276	210	176	153	140	102	98	95 [2970]		
			2		270	200	174	155	138	103 [1435]				
			3		281	207	176	155	144	103	98 [2390]			
			4		270	204	178	159	138	102	99	94	93	72 [7340]
			5		276	203	178	168	153	103	98	95	92 [5410]	
			6	Average Pulse Velocity	268 (3680)	203 (4900)	181 (5650)	155 (6350)	147 (7000)	104	98	96	92	
					3	4	5	6½	8					
2	151.1	2.5 inches	7		332	239	186	160	151	102 [1425]				
			8		326	230	186	161	145	103*	98	95 [3130]		
			9		305	225	183	160	144	103	99 [2430]			
			10		332	237	183	161	155	102	97	95	93 [5410]	
			11		296	230	180	163	142	102	98	96	92	
			12	Average Pulse Velocity	288 (3190)	215 (4360)	172 (5500)	159 (6210)	142 (6830)	102 (9750)	96 (10,200)	94 (10,500)	93 (10,800)	

*[ ]Values within brackets are compress strengths, psi, of cylinders broken at the given age.

TABLE 5

PULSE VELOCITY & COMPRESSIVE STRENGTHS AT DIFFERENT AGES

DESIGN MIX C

Batch	Unit Wt.	Slump	Cylinder #	Age, hrs	4-3/4	5½	6½	7	7½	8	12½	24	3 day	7 day	28 day
					Transmission Time in Microseconds										
1		1.5 inches	1		223	188	166	166	156	146	122	106 [1730]			
			2		197	174	162	156	159	153	120	105	97	94	90
			3		210	175	159	154	151	145	118	106	98 [2750]		
			4		212	184	164	164	155	149	131	106	98	95	93
			5		215	190	165	162	157	157	135	105	99	95	90 [5540]
			6	Average Pulse Velocity	224 (4680)	189 (5460)	163 (6130)	160 (6240)	155 (6430)	148 (6680)	118 (8060)	105	98	94 [3380]	
					4½	5	6	6½	7	7.5	12				
2	Not Recorded	1.5 inches	7		267	218	184	173	175	166	138	106 [1550]			
			8		278	220	184	178	174	171	139	108*	98	95 [3150]	
			9		291	233	213	196	196	183	132	109	98 [2630]		
			10		286	224	180	174	167	160	132	106	98	94	92
			11		252	211	173	164	156	153	118	105	96	93	89
			12	Average Pulse Velocity	272 (3640)	217 (4530)	183 (5370)	180 (5630)	185 (5700)	176 (5950)	138 (7530)	106 (9440)	96 (10,200)	95 (10,600)	90 [5320] (11,050)

*[ ] Values within brackets are compressive strengths, psi, of cylinders at the given age.

TABLE 6

PULSE VELOCITY & COMPRESSIVE STRENGTHS AT DIFFERENT AGES

DESIGN MIX O

Batch	Unit Wt.	Slump	Cylinder #	Age, hrs.	3½	6¼	8¼	24 hrs	24 hrs	3 day	7 day	28 day
					Transmission Time in Microseconds							
1	151.4	6.5 inches	1		560	221	177	107	108			90
			2		525	224	183	112	108		98 [1520]	
			3		470	212	171	107	106	94 [1080]		
			4		500	226	180	113	108 [640]			
			5		485	222	183		107	94		91 [2380]
			6		500	220	175		106	95	96	89
				Average Pulse Velocity	(1940)	(4520)	(5620)			(10,520)	(10,300)	(11,200)
					3	5-3/4	7½					
2	151.4	7.0 inches	7		505	245	200	114	109	97		89
			8		545	256	206	122	108		98	
			9		490	219	172	106	106	94		89 [2380]
			10		510	242	177	105	107			
			11		510	253	197		107		97 [1460]	89 [2180]*
			12		500	228	185		107	95 [1140]		
				Average Pulse Velocity	(1920)	(4160)	(5270)		(9350)	(10,520)	(10,300)	(11,200)

*[ ] Values within brackets are compressive strengths, psi, of cyliners broken at the given age.

TABLE 7

PULSE VELOCITY & COMPRESSIVE STRENGTHS AT DIFFERENT AGES

DESIGN MIX E

Batch	Unit Wt.	Slump	Cylinder #	Age, hrs	2½	4	5	6	6½	7	8	8½	24* hrs.	3 day	7 day	28 day
					Transmission Time in Microseconds											
			1		1015	422	271	206	197	188	167	166	101 [1080]	98 [1715]		
			2		1006	394	265	198	185	170	157	156	101			
1	152.5	5.5 inches	3		1075	451	298	210	190	183	168	160	100		94 [2430]	
			4		990	394	273	207	188	185	169	165	101			88 (11,350)
			5	Average Pulse Velocity	(975)	(2400)	(3610)	(4850)	(5260)	(5500)	(6060)	(6170)	102	99	95	88
			6										100 (9900)	(10,200)	(10,620)	88 [4600]
					2½	3½	4½	5½	6	6½	7½	8				
2	152.5	5.5 inches	7		930	447	310	223	205	185	166	163	102		93	88 [4500]
			8		865	472	280	216	197	188	168	163	102 ** [1030]			[3395]
			9		1075	526	306	221	204	180	172	165	99	98 [1715]		88
			10		1010	468	294	229	214	193	166	166	101	98		
			11	Average Pulse Velocity	(1030)	(2060)	(3360)	(4500)	(4870)	(5430)	(5950)	(6100)	101			88 (11,350)
			12										101 (9900)	(10,200)	94 [2345] (10,620)	

*Demolded

** [ ] Values within brackets are compressive strengths, psi, of cylinders broken at the given age.

TABLE 8

PULSE VELOCITY & COMPRESSIVE STRENGTHS AT DIFFERENT AGES

DESIGN MIX F

Batch	Unit Wt.	Slump	Cylinder #	Age, hrs	4½	5½	6-3/4	7½	12	24	3 day	11 day	14 day	28 day	454 day
					Transmission Time in Microseconds										
1	153.6	4.5 inches	1		195	167	154	151	131	103		91	89	89 [4310]	
			2		184	162	153	142	127	102		91	89	89	
			3		197	165	150	146	118	102	95 [2600]				
			4		193	163	152	146	124	101	94	90			
			5		197	163	154	145	121	102	96	91	[3815] 90	91	73 [8,260]
			6		188	157	159	149	125	101 [1780]					
				Average Pulse Velocity	(5210)	(6140)	(6500)	(6830)			(10,510)	(11,000)	(11,000)	(11,000)	
					4	5	6½	7½							
2	153.6	4.5 inches	7		236	168	160	144	126	102		91	90	91 [4510]	
			8		230	171	160	154	126	103 [1840]					
			9		235	176	154	142	123	102*	95	91	90	90	
			10		235	173	158	143	116	101	95	91	90	90	69 [8,260]
			11		238	174	157	145	126	102		91		[4095]	
			12		237	172	160	148	122	103	95 [2670]				
				Average Pulse Velocity	(4250)	(5810)	(6320)	(6850)	(8060)	(9800)					

*[ ] Values within brackets are compressive strengths, psi, of cylinders at the given age.

TABLE 9

PULSE VELOCITY & COMPRESSIVE STRENGTHS AT DIFFERENT AGES

DESIGN MIX G

Batch	Unit Wt.	Slump	Cylinder #	Age, hrs	3½	4½	5½	12	24 hrs	3 day	7 day	28 day
					Transmission Time in Microseconds							
1		3 inches	1		181	173	142	112	103	95	96	91
			2		183	180	144	115	103	97 [2740]		
			3		182	169	147	112	102 [2600]			
			4		171	183	143	109	104	98	95 [4280]	
			5		188	185	146	112	103	89		92 [5740]
			6		176 (5550)	172 (5650)	143 (6950)	113 (8930)	103	96	96	92
					3	4	5	12				
2	Not Recorded	2.75 inches	7		227	205	163	111	103	96 [2720]		
			8		216	198	160	112	105 [2620]			
			9		217	187	146	111	102 *	93	96 [3880]	
			10		196	195	147	112	102	97	91	91
			11		212	191	162	114	102	98	95	91 [5600]
			12		223 (4650)	211 (5050)	165 (6350)	114 (8930)	102 (9700)	97 (10,500)	94 (10,600)	90 (11,000)

*[ ]Values within brackets are compressive strengths, psi, of cylinders broken at the given age.

The transmission times, in microseconds, follow a definite pattern with the time diminishing (velocity increasing) with time. A typical curve for this change is shown in Figure 7 with the average of the transmission times used to determine the pulse velocity for each batch plotted versus the log of the age. Such a curve appears to be a means of following the development of hydration and it could be a means of determining a type of final set. This would be made by finding the intersection of the two separate portions of the curves. On Figure 7 this would be at approximately 15 hours.

When data of all mixes were compared for early ages it became evident that meaningful and practical determinations of concrete quality could not be made from pulse velocity determination at early ages.

At later ages pulse velocity was measured immediately prior to compression testing of specimens. The results are shown in Figure 8 and as expected a pulse velocity did not correspond to any given concrete strength. A general trend is evident but the intermingled points for different mixes illustrate that pulse velocity does not promise to be a good quality control measurement for concrete in construction.

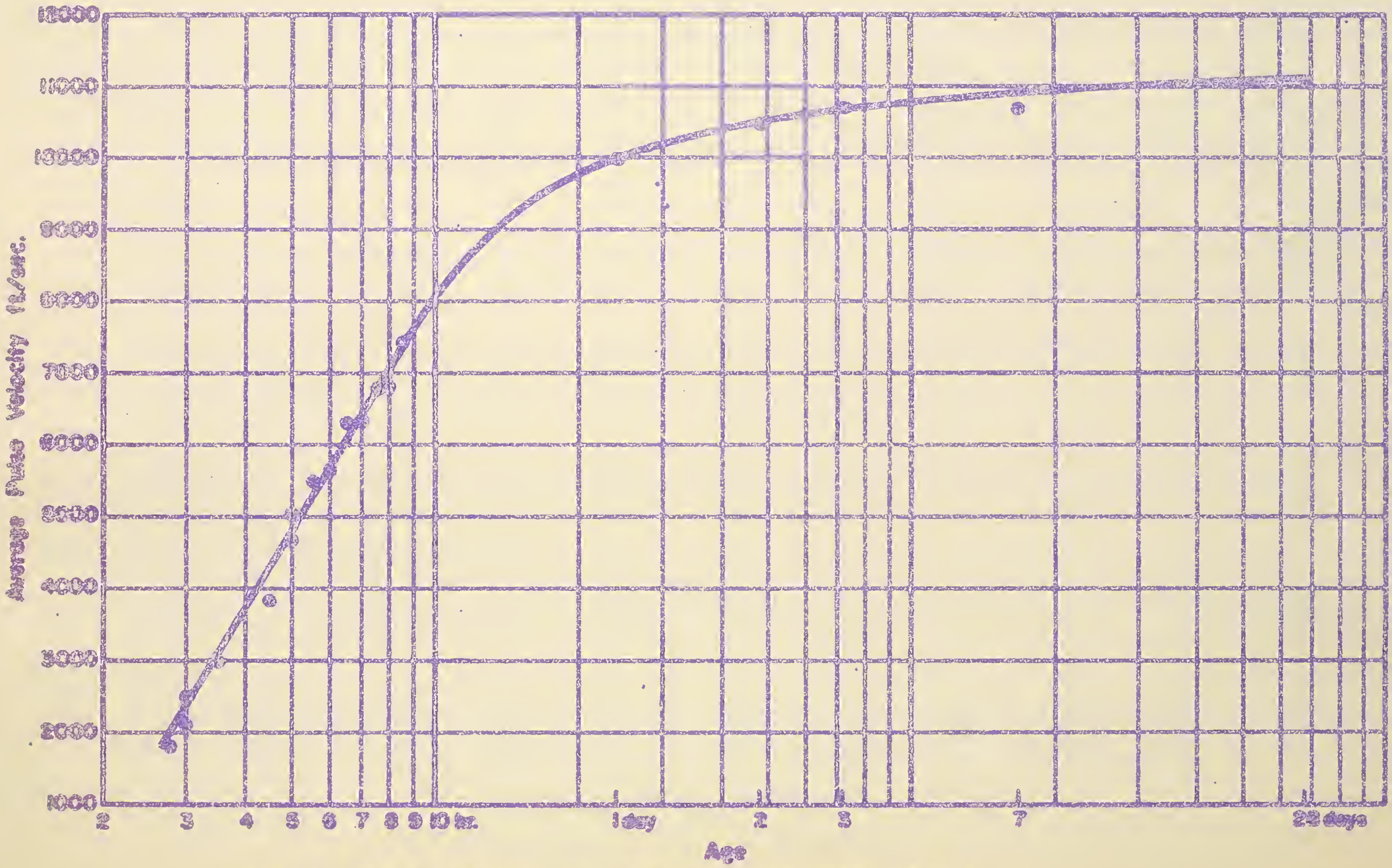


Fig. 7 - Pulse Velocity vs. Age of Concrete, Mix A

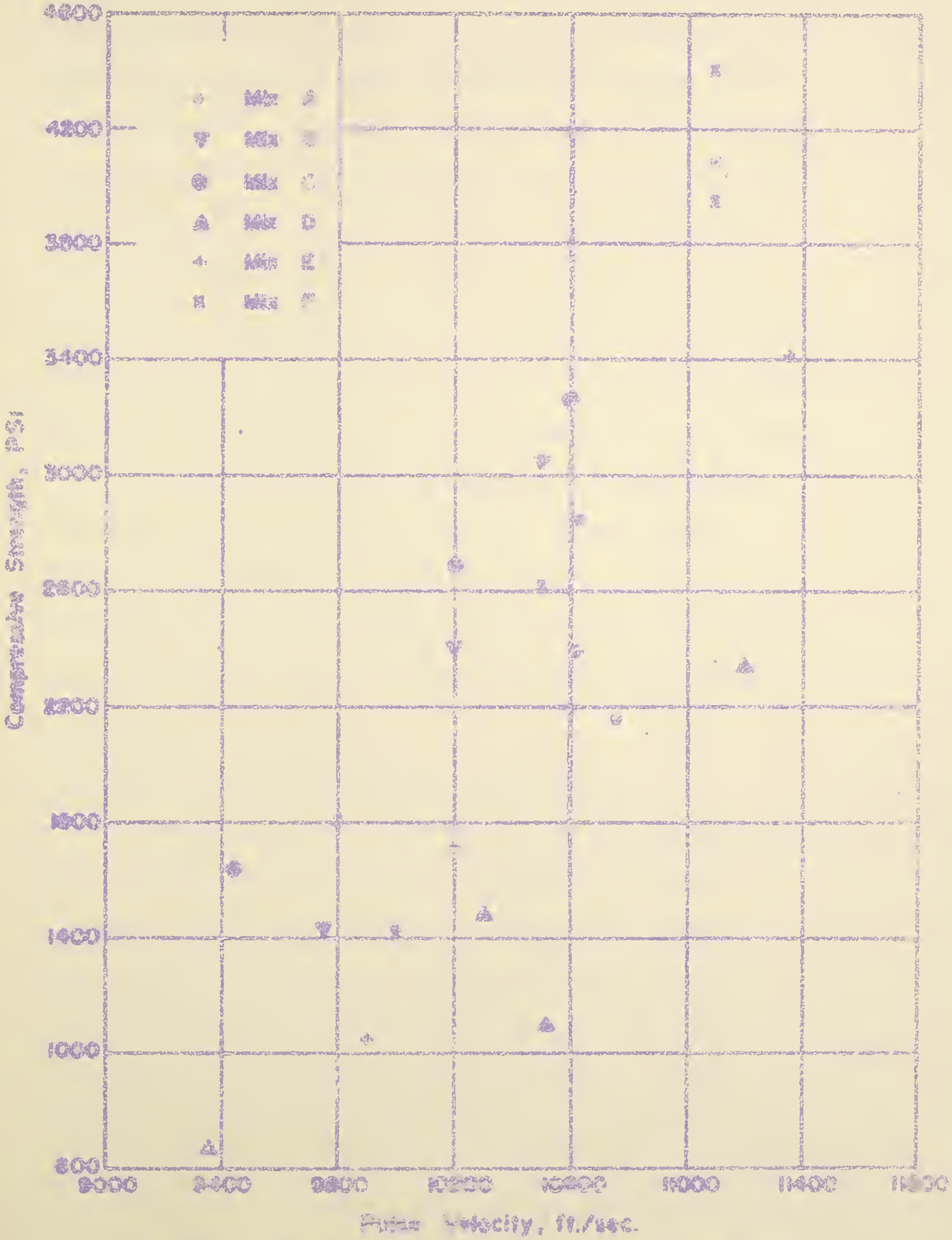


Fig. 8 - Compressive Strength vs Pulse Velocity

Evaluation of Bridge Decks

A field investigation of the usefulness of pulse-velocity equipment, the V-Scope, in establishing the extent of horizontal lamination in bridge decks was conducted in cooperation with the Indiana State Highway Commission's Research and Training Center. Their personnel conducted a number of tests on bridge decks with the transducers placed on opposite sides, top and bottom, of the deck, hence they measured directly through the deck. They were able to establish areas with reduced velocities which proved to be the limits of delamination when maintenance crews removed upper portions of the concrete deck which was not intergral with the remainder of the decks.

The use of this procedure necessitated access to the bottom of the slab. On some structures this can present considerable problems. In any case, it is a reliable way of assuring continuety of concrete. Unsound concrete, as well as cracks or void areas in otherwise sound concrete can be determined by this procedure.

Influence of Reinforcing Steel on Pulse Velocity

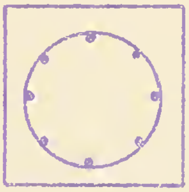
A question frequently asked by engineers contemplating applications of pulse velocity measurements in concrete has been: What is the influence of reinforcing steel on pulse velocity measurements through reinforced concrete? To establish whether or not reinforcing steel was a factor a small laboratory investigation was conducted. Concrete specimens having steel varying from 0 to 6% by volume of the

specimen were utilized.

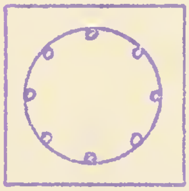
Each specimen was 12 inches by 12 inches at the base with a height of 18 inches. The concrete mix proportions are designated as mix H in Table No. 2. Four specimens were made with the steel tied with No. 9 wire and arranged as follows:

Mix 1: No steel

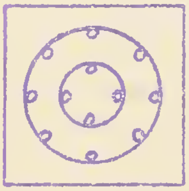
Mix 2: Eight No. 5 bars



Mix 3: Eight No. 8 bars



Mix 4: Twelve No. 8 bars



The specimens were cured with damp cloth and plastic for two weeks then left unprotected in the laboratory for fourteen months before the pulse velocity readings were made.

Pulse velocity measurements were made from five locations on each side through the specimen to its corresponding location

on the other side. A total of ten paths, were measured through the 12 inch dimension of the specimen. Measurements were also made with receiver and transmitter transducer positions reversed. Measurements were repeated on three different days with the result that six measurement were made on each path.

Readings were consistantly within several microseconds on all specimens, ie. they ranged between 72 and 76 microseconds. The average pulse velocity measurement of 13,500 feet per second for the nonreinforced specimen was also the average for the steel reinforced specimens including up to 6 percent steel by volume.

When measurement paths were between top and bottom of the specimen, ie. parallel to the steel, the results were nearly as consistant but the velocities were nearly 1000 feet per second greater than those through either the non-reinforced specimen or measurements transverse to the steel.

It was concluded from this work that the pulse velocity measurements of concrete are not appreciably influenced by reinforcing steel which crosses the path through which the measurement is made.

Summary of Applications

Throughout this project the establishment of applications of this equipment to highway uses has been the prime goal. Some portions of the project have indicated potential applications of real benefit while others have not. Both positive and negative results are hopefully of value when used as a guide to the efficient use of this equipment and development of other equipment.

Non-destructive pavement thickness determinations cannot be made with sufficient accuracy to warrent the use of this equipment for such purposes on pavement slabs on grade.

Resonant frequency tests and determination of dynamic Youngs modulus may easily be determined with the equipment. Of special merit is the use of the pulse velocity apparatus on inplace materials to find the dynamic Youngs modulus.

Pulse velocity was not found to be an acceptable method for evaluating fresh concrete during construction or as a measure of compressive strength at later ages.

Pulse velocity is an excellent means of determining the continuity of concrete. Cracks, voids or general deterioration will reduce the velocity. For this reason, it was successfully used in describing areas of a bridge deck which needed major repairs due to horizontal lamentation in the deck.

Reinforcing steel in conventional quantities and fabrication does not change the pulse velocity measurements obtained on concrete.

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